EFFECTIVE DISCHARGE AND THE DESIGN
OF CHANNEL MAINTENTANCE FLOWS
FOR GRAVEL-BED RIVERS

Effective Discharge and the Design of Channel Maintenance Flows for Gravel-Bed Rivers

by

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ABSTRACT

Water resource developments which deplete the quantity or reduce the range of streamflows usually have a number of unintended effects on the channel downstream, including loss of channel capacity, loss of aquatic and riparian habitat, and channel instabilities. A method for identifying a flow regime sufficient to maintain desired stream characteristics, while permitting significant development, would have great practical value. Over the past decade, important advances have been made in our understanding of fluvial processes in gravel-bed streams. Using these advances as a basis, one can outline a method for determining channel maintenance flows for gravel-bed streams typical to the western United States. A common characteristic of gravel-bed streams is that bed particles are transported only about 5-10 percent of the time during the highest flows, and, even then, at a very low rate. Although occasional motion of bed particles begins at a discharge as small as 60 percent of the bankfull value, general motion of the bed surface is exceedingly rare. The proposed method relies on an appropriate bedload transport function and specific reach information to compute the quantity of bed material in each size fraction transported by increments of discharge in the pre- and post-regulation regimes. Evaluation of possible flow regimes indicates that bankfull channel capacity can be maintained in its pre-regulation condition where as much as 60 percent of the natural flows are diverted.

INTRODUCTION

Alteration of natural streamflows by regulation and diversion is common throughout the arid western United States. Indeed, there are relatively few streams with drainage areas greater than a hundred square kilometers even in mountainous regions that have not been affected substantially. The most significant change in the natural streamflow regime is a decrease in the magnitude of annual peak flows, commonly by a factor of 2 to more than 10, Hirsch et al. (1990). An associated, although frequently unintended, consequence of streamflow storage and diversion is an appreciable change in quantity and size of sediment supplied to the stream channel. These changes, together with more diffuse, but often extensive, land use changes have greatly altered the quantity, seasonal distribution, and relative proportion of water and sediment supplied to stream channels throughout the western United States.

When streamflow and sediment supply are substantially altered over a period of years to decades, changes in the stream channel, floodplain, and riparian margin are common. The adjustment may include changes in channel size, morphology, pattern, rate of channel migration, bed-material particle-size distribution, floodplain morphology, and the composition and density of riparian vegetation, e.g., Petts (1979), Galay (1983), and Williams and Wolman (1984). Frequently, these adjustments affect downstream aquatic and riparian resources. Increased frequency of flooding due to reduced channel size and floodplain storage, loss of ecological habitat in the stream channel and adjacent floodplain, as well as the impairment of recreational and esthetic resources commonly occur following

substantial modification to the magnitude and frequency of natural streamflows.

The need and desire to minimize or avoid alteration of the stream channel and floodplain downstream from water storage and diversion facilities arise in nearly every instance. Typically, the loss of aquatic and riparian resources involve significant costs and foregone opportunities. In many instances, the stream and riparian resources are subject to state and federal statutes, e.g. National Environmental Policy Act of 1969, Clean Water Act of 1972, Endangered Species Act of 1973, Federal Land Policy and Management Act of 1976, and National Forest Management Act of 1976. State and federal courts have provided water rights for streamflows needed to achieve the objectives for which lands were reserved from the public domain, i.e. National Parks, Indian Reservations, etc. Thus, the design and operation of streamflow storage and diversion facilities invariably will include an analysis of the relation between flows and the nature of the stream channel and floodplain. That is, what quantity and distribution of streamflows throughout the year are required, together with a given contribution of sediment, to construct and maintain the channel and riparian resources of a particular reach? (See Rosgen et al. 1986 and Reiser et al. 1989 for examples of instream flow regimes formulated to maintain desired channel features.) Conversely, what portion of the natural streamflow may be stored or diverted without causing an unacceptable impairment of fluvial resources? These questions concern the fundamental issues of fluvial geomorphology and river mechanics. Clearly, the answers will have great practical significance in the management of water resources.

The concept of a dominant discharge has existed for decades in the hydrologic literature. The design of canal channels which would carry a specific discharge and a sediment load of silt, clay and fine sand without deposition or erosion was studied intensively in the 19th century, (Ackers, 1972). The relation between discharge and the characteristics of a natural channel are much more complex, Leopold and Maddock (1953). Stream discharge varies over a considerable range from extreme low flow to extreme flood. In addition, the range of sediment particle sizes in a naturally stream channel is typically much greater. The characteristics of naturally formed stream channels reflect this variability. Thus, one must consider a range and frequency of occurrence for the channel-forming flows rather than a single discharge.

Wolman and Miller (1960) developed a conceptual model to describe the influence of flow magnitude and frequency on the relative sediment transporting effectiveness of various discharges in natural channels. This model has become one of the fundamental paradigms of geomorphology. The Wolman-Miller model is illustrated by figure 1. The variation in sediment transport with discharge is represented by curve A. Sediment transport begins when discharge attains a threshold value, and then increases rapidly and continuously. The threshold discharge depends to a substantial degree on the size of sediment particles composing the channel bed and banks. Relatively small sediment particles, silt and fine sand, will be transported to some extent even at very small discharge in most river channels. Conversely, relatively large sediment particles, gravel and boulders, typically will only be moved by the quite large and uncommon discharges. Because transport rate is strongly influenced by particle size, it

is usually desirable to calculate separate sediment transport relations for each particle size class. The frequency of discharges in a given stream reach is described by curve B, which represents all discharges from extreme low flow to extreme flood. The product of these two relations gives a third curve, C, which is the frequency distribution of sediment transport, i.e. the percent of time a specific sediment transport rate has or will occur. Integrating the frequency of sediment transport rates over a period of time, typically one year, equals the total quantity of sediment transported.

The principal result of this model is that most of the sediment transported over a period of time is carried by a range of intermediate discharges. Discharges less than the threshold required for initiation of sediment motion transport no sediment. Discharges only somewhat greater than the threshold discharge may be quite common, but transport sediment at such a small rate that they carry only a small quantity of sediment over a period of years. The very largest discharges transport sediment at an exceedingly high rate, however, they occur so infrequently, perhaps only a few hours per century, that they carry only a small portion of the total quantity of sediment transported over a long period of time. The most effective sediment transporting discharges over a period of years are those which transport sediment at a moderately high rate and occur as frequently as a few days per year.

The specific shape and characteristics of the sediment transport function, A, and the frequency of discharges, B, vary greatly from river to river. Thus, the range and occurrence of the most effective sediment transporting discharges also vary greatly from one river to another. At one

extreme are those rivers which carry some sediment at even the smallest discharge and do not have a particularly wide range of floods. In such streams, effective discharges may occur for several weeks to perhaps months per year. At the other extreme are those rivers where only relatively rare, extreme floods are sufficient to move the available sediment particle sizes. In such streams, the range of effective sediment transporting discharges may occur only a few days per century.

The Wolman-Miller model for magnitude and frequency of effective sediment transport discharges has been evaluated by numerous investigations, (Pickup and Warner, 1976, Baker, 1977, Wolman and Gerson, 1978, Newson, 1980, and Miller, 1990). Nash (1994) found 138 citations to the original paper between 1960 and 1990. The vast majority of the instances where the model has been evaluated using field measurements have considered only suspended sediment transport. Measured suspended sediment concentration, in some cases collected daily, are available for several gaging stations in the United States over periods of as long as 40 years. These comparisons typically agreed quite well with the model. There is a well-defined range of relatively frequent discharges which transport most of the suspended sediment over a period of years. Furthermore, the duration of the effective discharge commonly varies from several days per year to perhaps one day in several years, (see Wolman and Miller, 1960, and Pickup and Warner, 1976).

Evaluations of streamflow magnitude and frequency based upon suspended sediment transport consider 90 percent or more of the sediment transported out of a drainage basin and, thus, are probably a good

approximation of the effective discharges for watershed denudation. Such evaluations, however, are not appropriate tests for the second hypothesis of the Wolman-Miller model, namely that the effective discharges are the channel-forming discharge, because most of the suspended sediment is finer than the material composing river bed and banks. This distinction is especially significant for gravel-bed rivers where clay, silt, and fine sand commonly represent 90 percent of the total sediment load and are transported in suspension even at relatively small discharges, whereas the river bed and banks consist of much coarser sized particles that may only be transported by flows equalled or exceeded a few days or less per year.

Analysis of bed-material transport magnitude and frequency in gravel-bed rivers has been limited due to substantial uncertainty in the transport rate at a specific discharge. Extensive bedload transport measurements have been made at relatively few sites, approximately 10, in North America, and then only for a period of a few years to at most a decade or so, (Milhous, 1973, Leopold and Emmett, 1976, Jones and Seitz, 1980, and Andrews, 1994). Thus, one must rely upon establishing a relation between flow and bedload transport rate, which can then be applied over a longer period of recorded discharges. For some of the bedload measurement sites, however, the period of record for discharges are insufficient to adequately define the frequency of moderately large to extreme flows. Given the very large commitment of funds and time needed to measure bedload transport rates in a gravel-bed river over a wide range of relatively large discharges, it is improbable that there will be a significant number of sites where the magnitude and frequency of measured bedload transport will be determined solely from measurements.

Accordingly, the analysis of bedload transport magnitude and frequency must rely, to a substantial degree, upon calculated transport rates at streamflow gaging stations with long periods of record. This is the approach taken by the investigation described herein. The approach depends upon the ability to predict these bedload transport rates in gravel-bed rivers to a reasonable degree of accuracy.

The primary objective of this study is to formulate a regime of streamflows sufficient to maintain the existing bankfull channel for a given quantity and particle size distribution of sediment supplied to the channel. The approach is to analyze the magnitude and frequency of bed-material transport in gravel-bed rivers that are typical of the western United States, and determine whether the bankfull channel is related to the range of effective transporting discharges. This approach is, in fact, an evaluation of the Wolman-Miller hypotheses as they apply to gravel-bed rivers. A second objective concerns only the bankfull discharge, i.e. the conveyance of the naturally formed channel. In many, perhaps most instances, other channel attributes, e.g. channel sinuosity or relative pool depth, also may support significant or essential resources. Maintaining a given bankfull channel by providing the regime of streamflows necessary to move the several sizes of particles present in the bed and banks may not be sufficient to maintain the aquatic and riparian resources one might desire to preserve in a given stream reach. Additional mechanical or fluid dynamical processes as well as biological activity may be essential to form and maintain particular channel resources. Thus, the streamflow regime that preserves the

magnitude and frequency of transport rate is a necessary, although perhaps not a sufficient condition for maintaining all channel resources.

CHARACTERISTICS OF RIVER REACHES STUDIED

The basic hypothesis of the Wolman-Miller model and the principle which this study relies upon to design a regime of channel maintenance flow is that similar river channels will have similar magnitudes and frequencies of transport rates. Conversely, differences between stream channels are a consequence, wholly or in part, of different magnitudes and frequencies of transport rate. Accordingly, the appropriate test of this hypothesis must concern a group or class of identifiable, i.e. similar, rivers and streams. For this study, single-thread gravel-bed rivers with mobile beds and stable banks have been selected, because they are common throughout the mountainous areas of the western United States and frequently subject to extensive flow regulation and diversion.

Andrews (1984) determined the hydraulic geometry relation of 24 gaging stations located on gravel-bed rivers in Colorado. Most of the information required to determine the magnitude and frequency of transport had been collected at these gaging stations. Eleven streams considered in the previous study were eliminated for various reasons, including a relatively short period of record, appreciable quantities of sand in the bed-material, or a complicated stage-discharge relation affected by the backwater of a tributary. Four river reaches not included in the previous investigation have been added.

All of the stream reaches studied are in mountainous parts of Colorado and are typical of alluvial gravel-bed streams throughout the Rocky Mountain region. Several geomorphic factors, including bed and bank material, floodplain development and long-term stability of the riverbed elevation were considered when selecting the study reaches. The channel bed and banks were composed primarily of sediment transported and deposited by fluvial action. Many reaches contain a small fraction of very coarse material, including boulders, which did not appear to be moved by the stream except perhaps during the most extreme floods. A well-defined floodplain indicative of the bankfull elevation was an essential characteristic of all reaches selected for study. Although the floodplain was well-defined along all streams, floodplains frequently were discontinuous and had limited areal extent. In each study area, three to five cross sections were surveyed in relatively straight parts of the reach. Longitudinal profiles of the water surface and bankfull elevation were also surveyed through a reach of approximately 30 channel widths that included a streamflow-gaging station. The bankfull discharge of the reach was determined from the bankfull longitudinal profile and the stage-discharge relation at the gage. The bankfull hydraulic characteristics of the several cross sections were calculated using the surveyed bankfull cross sections, the bankfull discharge, and mean reach slope. The size distribution of the riverbed surface was determined by a random sampling method (Wolman, 1954). The study reaches and their associated hydraulic and bed-material transport characteristics are summarized in Table 1.

Table 1. Measured and computed bed-material transport and hydraulic characteristics at selected gravel-bed rivers.

USGS station number	Station name	Period of Record (water years)	Drainage Area (km)^2	Mean Annual Discharge (m^3/sec)	Bankfull Discharge (m^3/sec)	Duration of Bankfull Discharge (%)	Effective Discharge (m^3/sec)	Mean Annual Bedload Transport (Ton/yr)
06614800	Michigan River nr. Cameron Pass	1974-93	3.96	0.086	0.70	1.76	0.73	660
06620000	North Platte River nr. Northgate	1916-93	3706	12.3	85.2	1.21	88.4	67
06724500	Lefthand Creek nr. Boulder	1930-31, 1947-53, 1956-57, 1977-80	135	1.06	4.9	3.53	4.82	1400
06725500	Middle Boulder Creek at Nederland	1908-93	93.7	1.53	9.5	1.74	9.9	2300
06748530	Little Beaver Creek nr. Rustic	1961-73	31.9	0.23	1.6	2.10	1.56	290
06748600	South Fork Cache La Poudre River nr. Rustic	1957-79	239	1.80	9.4	3.25	10.3	770
07083000	Halfmoon Creek nr. Malta	1947-93	61.1	0.82	7.08	0.42	5.27	1380
09022000	Fraser River at upper station nr. Winter Park	1969-73, 1985-93	27.2	0.40	2.69	1.70	2.69	160
09035900	South Fork Williams Fork nr. Leal	1966-93	70.5	0.92	8.36	0.32	5.86	1080
09036000	Williams Fork nr. Leal	1940-93	231	2.72	22.6	1.1	23.5	210
09074800	Castle Creek above Aspen	1970-93	83.4	1.23	4.45	6.51	4.39	6200
09078100	North Fork Fryingpan River abv. Cunningham Creek nr. Norrie	1964-78	31.1	0.55	3.17	4.66	3.74	16
09078200	Cunningham Creek nr. Norrie	1964-78	18.4	0.29	2.52	1.73	2.48	150
09081600	Crystal River abv. Avalanche	1956-93	433	8.44	49.0	2.63	55.8	210
09124500	Lake Fork at Gateview	1938-93	865	6.68	42.0	1.77	46.4	120
09249750	Williams Fork at mouth nr. Hamilton	1985-93	1085	5.83	46.7	1.18	49.0	130
09253000	Little Snake River nr. Slater	1944-93	738	6.46	72.2	0.37	55.4	84

Bankfull discharges range from 0.70 to 85.2 m^3/sec. Median bed-material sizes vary from 24 to 91 mm, and bankfull water surface slopes vary from 0.0014 to 0.26. Computed mean annual bed-material loads are generally small relative to the contributing drainage area and vary from 0.02 to 166 ton/km^2 - year.

The seventeen reaches were selected for study based upon a well-defined bankfull channel in the vicinity of the gaging station, as well as an appreciable period of record uninterrupted by flow diversion and storage. The natural streamflow regime of approximately one-half of the study reaches has been altered to some degree by flow depletion. In all instances, these developments have existed for several decades during which the channels will have adjusted to the altered regime. The period of records shown in table 1 refer to a generally constant extent of streamflow alteration.

COMPUTATION OF BED-MATERIAL TRANSPORT RATE

Parker et al. (1982) formulated an empirical bedload transport function for poorly-sorted of gravel and cobbles. The Parker bedload function is

$$W^*_i = \begin{cases} 0.0025 \exp\left[14.2 (\phi_i - 1) - 9.28 (\phi_i - 1)^2\right]; \; 0.95 < \phi_i < 1.65 \\ \end{cases} \qquad (1)$$

$$11.2\left(1 - \frac{0.822}{\phi_i}\right)^{4.5} \qquad \phi_i > 1.65$$

where

$$W^*_i = \frac{q_{bi}(\gamma_s/\gamma - 1)}{f_i\, g^{1/2}\, (RS)^{3/2}}$$

and

$$\phi_i = \frac{\tau_i^*}{\tau_{ri}^*}$$

in which q_{bi} is the volumetric bedload transport rate of the i^{th} particle fraction per unit width of channel, f_i is the percent of bed particles in the i^{th} fraction, and g is the acceleration of gravity.

An essential aspect of this approach was the development of a reference dimensionless shear stress, τ^*_{ri}, such that $\tau^*_{ri} = f\,(d_i/d_{50})$ where d_i is the diameter of particles of the i^{th} size fraction of bed material and d_{50} is the median particle diameter of bed material. Parker et al. (1982) found that the use of ϕ_i, rather than τ^*_i, resulted in a similarity collapse, so that W^*_i is approximately a single valued function of ϕ_i. The Parker bedload function for the domain $\phi_i > 1.65$ was derived by fitting ϕ_i and W^*_i to the Einstein bedload function. For the domain $0.95 < \phi_i < 1.65$, the Parker bedload function was derived from bedload transport rates measured in Oak Creek (Milhous, 1973).

As formulated, equation (1) should apply to any mixture of gravel-sized material, from uniform to poorly-sorted, so long as the reference shear stress correctly represents the response of the bed material to the fluid forces (i.e. when $\phi_i = 1$, then $W^*_i = 0.0025$). Therefore, equation 1 should be generally applicable. The relation $\tau^*_i = f(d_i/d_{50})$, however, may vary from stream to stream depending upon the nature of the bed material, particle size-distribution, shape and packing. The extremely steep slope of the ϕ_i vs W^*_i relation, when $\phi_i \leq 1.65$, however, means that relatively small errors in the reference shear stress, τ^*_{ri}, will lead to substantial errors in the predicted bedload transport rate. Thus, determination of the correct values of τ^*_{ri} for a given mixture of bed particles is essential, especially when calculating marginal bedload transport rates.

Parker et al. (1982) determined the dependence of τ^*_{ri} on d_i/d_{50} for Oak Creek by calculating the value of τ^*_{ri} at a dimensionless transport rate of $W^*_i = 0.0025$. The particle size distribution of subsurface bed material was used for most of the analysis of Oak Creek. Their approach, however, is not limited to the subsurface material. The size distribution of surface bed material can be used, and is equally valid, (Andrews and Parker, 1987). The median particle size of surface bed material is used to scale the relative particle protrusion because it represents the assemblage of bed particles from which the bedload material is derived, (Wiberg and Smith, 1987, Wilcock and McArdell, 1993, and Andrews, 1994). This approach avoids the need to assume that the particle size distribution of bedload and subsurface material are similar.

Wilcock and Southard (1988), Kuhnle (1992), and Andrews (1994) have taken a slightly different approach than Parker et al. (1982) used to determine the function $\tau^*_{ri} = f(d_i/d_{50})$. Instead of calculating the value of τ^*_{ri} at $W^*_i = 0.0025$, they varied τ^*_{ri} to obtain the best fit of equation 1 to a wide range of measured transport rates of each i^{th} size fraction. Bedload transport rates have been measured at three of the river reaches selected for this analysis, Middle Boulder Creek at Nederland, Lefthand Creek nr. Boulder, and South Fork Cache La Poudre River nr. Rustic. Using these measurements, the variation of τ^*_{ri} with (d_i/d_{50}) was determined for each site. The empirically determined functions, $\tau^*_{ri} = f(d_i/d_{50})$, are shown in figure 2 together with the previously determined functions for Oak Creek, (Parker et al., 1982) and Sagehen Creek (Andrews 1994). The respective equations are

$$\tau^*_{ri} = 0.033\,(d_i/d_{50})^{-0.982} \tag{2}$$

for Oak Creek,

$$\tau^*_{ri} = 0.0384\,(d_i/d_{50})^{-0.887} \tag{3}$$

for Sagehen Creek nr. Truckee, CA,

$$\tau^*_{ri} = 0.0354\,(d_i/d_{50})^{-0.975} \tag{4}$$

for Middle Boulder Creek at Nederland,

$$\tau^*_{ri} = 0.0376\,(d_i/d_{50})^{-0.994} \tag{5}$$

for Lefthand Creek nr. Boulder,

$$\tau^*_{ri} = 0.035\ (d_i/d_{50})^{-0.942} \qquad (6)$$

for the South Fork Cache La Poudre River nr. Rustic.

Among the five relations, the one determined for Middle Boulder Creek at Nederland, is the nearest to an "average" relation over the range of (d_i/d_{50}) values. For a given ratio $(d_i/_{50})$, values of the referenced dimensionless shear stress determined for the 5 streams vary no more than ±10 percent from the Middle Boulder Creek relation, see figure 2.

Bed-material transport rates for particle size fractions from 4mm-180mm over the range of recorded discharges were computed for the 17 sites using the Parker bedload function. The reference shear stress function, equation 5, determined for Middle Boulder Creek was applied for all sites, except Lefthand Creek and the South Fork Cache La Poudre where the site-specific functions were applied.

Sensitivity of the computed magnitude and frequency of bed-material transport to uncertainty in the measured reach hydraulic characteristics and the streamflow regime due to an insufficient period of record were evaluated using the Middle Boulder Creek gage. This gage was selected for the sensitivity analysis because the most extensive measurements of bed-material transport and the longest period of record have been collected there.

EFFECTIVE BED-MATERIAL TRANSPORTING DISCHARGES

The quantity of bed-material in each particle size fraction transported by increments of discharge over the period of record at each gaging station may be determined either by calculating the quantity of bed material transported each day during the period of record or by the flow duration - sediment transport method. Both approaches will give the same result, and have been used in this study. Calculating the quantity of bed-material day-by-day preserves valuable information concerning temporal variability. In many instances, such as the evaluation of a proposed project, however, a flow duration relation will be more readily available and reliable than a time series of estimated daily values. The observed relation between dimensionless shear stress and discharge at a gage was combined with the bedload transport function for each particle size fraction. The duration of a given discharge increment over the period of record was multiplied by the quantity of bed material in a size fraction transported by the discharge per unit time. Results of these calculations at six gaging stations are summarized in figures 3a-f. The six graphs were chosen to illustrate the range of results. The several curves in each graph represent curve C in figure 1 for the identified particle size fractions. The area between adjacent curves is the mean annual quantity of bed material transported in the size-fraction. The mean annual quantity of bed material transported in all size fractions is the total area under the top curve.

In general, the range of significant bed-material transporting discharges is well-defined. Bed material begins to move on average at discharges approximately 60 percent of the bankfull discharge and 2-3 times

the mean annual discharge. Many of the effective discharge plots are skewed to the larger discharges; however, discharges greater than twice the effective value transport a relatively small fraction of the mean annual load. For all river reaches, the middle 80 percent of the mean annual load is transported, on average, by flows between approximately 0.8-1.6 times the bankfull discharge. For the 17 streams studied, the middle 80 percent of the mean annual bed-material load is transported on average during 15.6 days per year by discharges that represent 27 percent of the mean annual runoff and range from 17 to 40 percent of the mean annual runoff. On average, discharges less than bankfull transport 39 percent of the mean annual bed-material load.

The interval of discharge that transports the largest portion of the mean annual bed-material load over a period of years, i.e. the modal-value, is termed the effective discharge (Andrews, 1980). It should be noted that no special significance is attached solely to a single discharge. The effective discharge is a simple and straightforward representative for the range of discharges which transport the vast majority of the mean annual bed-material load over a period of years. The effective discharge computed for each river reach is listed in Table 1, and compared in figure 4 with the field-determined bankfull discharge. Generally, there is a good one-to-one agreement between the field-determined bankfull discharge and the computed effective discharge. The mean normalized difference between the effective and bankfull discharges is 11 percent. This result supports the Wolman-Miller hypothesis that river channel characteristics, and specifically, the capacity of the naturally formed channel, will be determined by the range of discharges that transport most of the bed-material over a period of

years. The close agreement between the effective and bankfull discharge for the 17 river reach study demonstrates that the range of effective bed-material transporting discharges are the flows which construct and maintain these channels.

The effect of uncertainty in the hydraulic characteristics of a reach was evaluated by varying the water surface slope by ±10 percent. This test also is equivalent to a ±10 percent change in the flow depth and median bed-material particle size. Uncertainty in the reach hydraulic characteristics has a very significant effect, as large as ±300 percent on the computed mean annual bed-material load, but only a very small effect on the effective discharge or range of dominant bed-material transporting discharge. The computed effective discharge is 9.09 m^3/sec using a 10 percent increase in water surface slope and 9.66 m^3/sec using a 10 percent decrease in water surface slope compared to 9.94 m^3/sec as shown in figure 3d.

As described above, the dominant bed-material transporting discharges, i.e. those discharges that transport the central 80 percent portion of the mean-annual bed-material load, occur about 15 days per year on average. There is, however, substantial year-to-year variation in the duration of bed-material transporting discharges and, correspondingly, the quantity of bed material transported. Years having relatively large runoff typically will have many more than the average number of days with discharge in the range of dominant bed-material transporting flows. Conversely, relatively small runoff years frequently will have few or no days of dominant bed-material transporting discharge. The accumulative distribution of days over the period of record when flow occurred within the

range of dominant bed-material transporting discharges are shown for the six gaging stations with the longest periods of record in figure 5a-f. The abscissa values were computed by ordering the annual runoff from smallest to largest and divided by the length of record. The ordinate values were computed by summing the number of days of dominant bed-material transporting discharge from the smallest to the largest annual runoff years and divided by the total number of days the dominant discharge occurred.

Approximately 50 percent of all days when the daily mean flow was within the range of dominant bed-material transporting discharges occur in about 20 percent of the years. Conversely, dominant bed-material transporting discharges did not occur during approximately one-third of the years. Those years when dominant bed-material transporting discharges occurred on a relatively large number of days were, with rare exception, years during which annual runoff significantly exceeded the long-term mean. For example, the 17 largest runoff years recorded at the Middle Boulder Creek at Nederland gage, 20 percent of the period of record, had 57 percent of all days with discharges within the range of dominant bed-material transporting flows. Furthermore, 51 percent of all bed material transported during the period of record, 1908-1993, occur in the17 largest runoff years.

Finally, an additional factor complicates a simple description of the occurrence of the dominant bed-material transporting discharges. In those years with several days of dominant discharge, the period of significant bed-material transport is frequently broken into two, three, and, sometimes, four segments of a few days each and occurring over a period of 30-40 days.

CHANNEL MAINTENANCE FLOWS

The preceding analysis has identified the magnitude and frequency of discharges which transport most of the bed-material load over a period of years in gravel-bed rivers common throughout the western United States. These discharges have a relatively narrow range, between 0.8 and 1.6 times the bankfull discharge, and occur approximately 15 days per year on average. Furthermore, the bankfull discharge of the rivers studied lies within the range of dominant bed-material transport discharges and is very nearly equal to the interval of discharge which transports the largest portion of the long-term bed-material load. Therefore, it is concluded that the dimensions, morphology, and other physical characteristics of these gravel-bed rivers are primarily determined by a well-defined, relatively narrow range of discharges. These results establish the basis for formulating a regime of streamflows which will substantially maintain the existing physical characteristics of these river channels when the natural streamflows are appreciably altered. The focus of our analysis will be the situation where natural streamflows are reduced; however, the approach is equally suitable for the situation where natural streamflows are increased. The following analysis and discussion will consider the issues and difficulties that arise in formulating a regime of channel maintenance flows.

Before proceeding, it is important to restate that the regime of channel maintenance flows is a necessary, but, perhaps, not a sufficient condition to maintain an existing channel. Additional factors frequently influence or determine specific characteristics of a channel.

The circumstances for which one would need to formulate a regime of channel maintenance flows are quite diverse. The availability of information describing the existing and future streamflows and supply of sediment to the channel will vary greatly. The ideal situation is the one in which detailed information exists concerning the natural flow regime, bed-material transport, as well as the type of structure and the manner of operation that will store or divert flow. With this information, magnitude and frequency of bed-material transporting discharges can be calculated directly for the reach of interest. The quantity of bed material supplied to the affected reach will depend upon the structure built to store or divert flow. A reservoir will usually trap all gravel sized material except where provisions for sluicing are incorporated into a dam. In contrast, flow diversion structures typically retain significantly less coarse sediment than a dam.

Formulating a practical operational regime of channel maintenance flows from an analysis of the magnitude and frequency of bed-material transport is not a simple exercise. The channel maintenance regime will be part of a development project whose primary purpose is to store and/or divert flow from the stream. Such projects inevitably involve significant economic, legal, and operational constraints on the possible instream flow regime. A proposed regime of channel maintenance flow will be evaluated and judged on whether the flows are (1) efficient and (2) predictable. An efficient regime will maintain the desired channel characteristics with the minimum quantity of water possible. The regime of channel maintenance flows also must be predictable. That is, the channel maintenance discharge

on a given day must be specified. The numbers of times when mean daily flow was within the range of the dominant bed-material transporting discharge on a given date over the entire period of record are shown in figure 6a-f, for several of the rivers considered in the study. As shown in figure 6a-f, even during that period each year when discharges are most likely to occur within the range of the dominant bed-material transporting flows, the probability of occurrence on any given day is less that 50 percent. For most of the snowmelt period, the probability of a dominant bed-material transporting discharge occurring on a given day is significantly less than 50 percent. Consequently, any channel maintenance regime structured to retain all streamflows for a specific period of time each year, for example May 15-May 31, will be inefficient most of the time, because the actual streamflow is less than the range of dominant bed-material transporting discharges. Such a regime is predictable; however, it is also inefficient because the flows retained in the channel during most years will be insufficient to transport appreciable quantities of sediment. Alternative channel maintenance regimes that are more efficient are less predictable. In fact, efficiency and predictability are in nearly all practical circumstances mutually exclusive. For the type of stream considered in this study, gravel-bed streams with snowmelt floods, any channel maintenance regime will require a balancing of efficiency and predictability.

As water supplies become more extensively developed and competition for aquatic resources intensifies, it seems certain that greater efficiency will be demanded at the expense of predictability. Accordingly, operation of a diversion or storage structure will become much more complex than is now the common practice. The principal consequences of

this shift will be a need to develop sophisticated diversion structures which can bypass the dominant bed-material transporting flows whenever they occur.

A highly efficient and effective channel maintenance flow regime would retain the historical magnitude and frequency of bed-material transport utilizing the least quantity of water. One possible channel maintenance regime for Middle Boulder Creek would be the natural flow whenever it is sufficient to move bed-material particles. In Middle Boulder Creek, bed-material transport begins at about $4.8 m^3/sec$, which is approximately 3 times the mean annual discharge and one-half of the bankfull discharge.

The resulting channel maintenance flow regimes are compared with the natural flow in figure 7 for 3 years, 1915 average runoff, 1954, below average runoff and 1957, well above average runoff. The channel maintenance flow regime has essentially the same magnitude and frequency of bed-material transporting discharge.

Over the entire period of record the proposed channel maintenance flows equal 35 percent of the long-term mean annual runoff. During 3 of the 85 years of record, natural daily mean flows did not exceed 3 times the mean annual discharge, and, therefore, under the proposed regime no channel maintenance flow would have occurred. Conversely, during several of the largest runoff years, the natural flow exceeded 3 times the mean annual flow for several weeks.

SUMMARY AND CONCLUSIONS

1. A method for determining a regime of channel maintenance flows that will preserve the physical characteristics of self-formed streams when an appreciable quantity of the natural flow is diverted or stored has been formulated. The method relies upon identifying the magnitude and frequency of bed-material transporting discharges in the natural channel, and then, retaining these flows following any modification of the natural flow regime.

2. To demonstrate this method, the magnitude and frequency of bed-material transporting discharges were computed for 17 gravel-bed rivers typical throughout the Rocky Mountain Region. The range of flow which transported the vast majority of bed-material over a period of years was generally well-defined. On average, those flows that transported the modal 80 percent of the long-term mean bed-material load ranged from 0.8 to 1.6 times of bankfull discharge and occurred 15.6 days per year. There are, however, substantial year-to-year variations in the duration of bed-material transporting discharge and correspondingly, the quantity of bed material transported.

3. The bankfull discharges of the 17 gravel-bed rivers are in excellent one-to-one agreement with the interval of discharge that carries the largest quantity of bed-material over the period of record. Based on this agreement it was concluded that the range of effective bed-material transporting discharges are the flows which construct and maintain these channels over time.

4. In practice, an operational regime of channel maintenance flow will involve a balancing between (1) minimizing the quantity of water required for instream flows, and (2) the predictability of these flows.

5. A highly efficient channel maintenance regime consisting of all flows sufficient to initiate bed particle motion and greater was evaluated. This regime would preserve the natural range of dominant bed-material transporting discharges with 35 percent of the mean annual flow. A substantial majority of channel maintenance flows, both number of days and volume, would occur during large runoff years. Little or no maintenance flows in excess of the baseflow would occur during years with below average runoff.

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FIGURE CAPTIONS

Figure 1. Wolman-Miller model showing the relative importance of magnitude and frequency of streamflows.

Figure 2. Comparison of reference dimensionless shear stress, τ^*_{ri}, versus relative particle protrusion (d_i/d_{50}) determined for five gravel-bed rivers.

Figure 3. Accumulative quantity of bed material in size fractions transported by increments of discharge in the (a) Williams Fork nr. Leal, CO; (b) North Platte River nr. Northgate, CO; (c) Little Snake River nr. Slater, CO; (d) Middle Boulder Creek at Nederland, CO; (e) Lake Fork nr. Gateway, CO; and (f) Halfmoon Creek nr. Malta, CO.

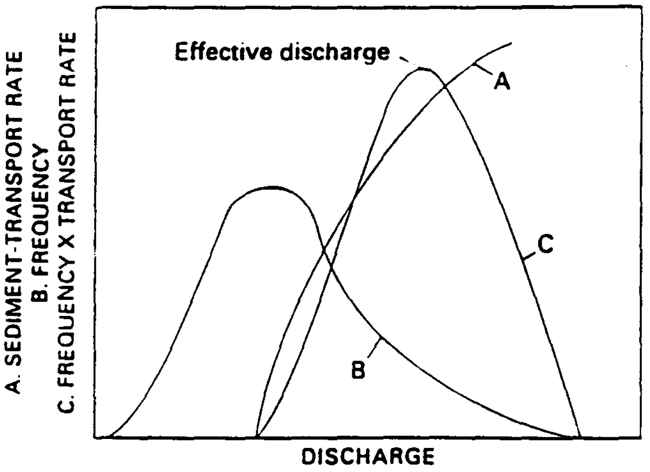
Figure 4. Comparison of effective discharge and bankfull discharge.

Figure 5. Accumulative distribution of days when dominant bed-material transporting discharges occurred during the period of record, (a) Williams Fork nr. Leal; (b) North Platte River nr. Northgate; (c) Little Snake River nr. Slater; (d) Middle Boulder Creek at Nederland; (e) Lake Fork nr. Gateway; and (f) Halfmoon Creek nr. Malta.

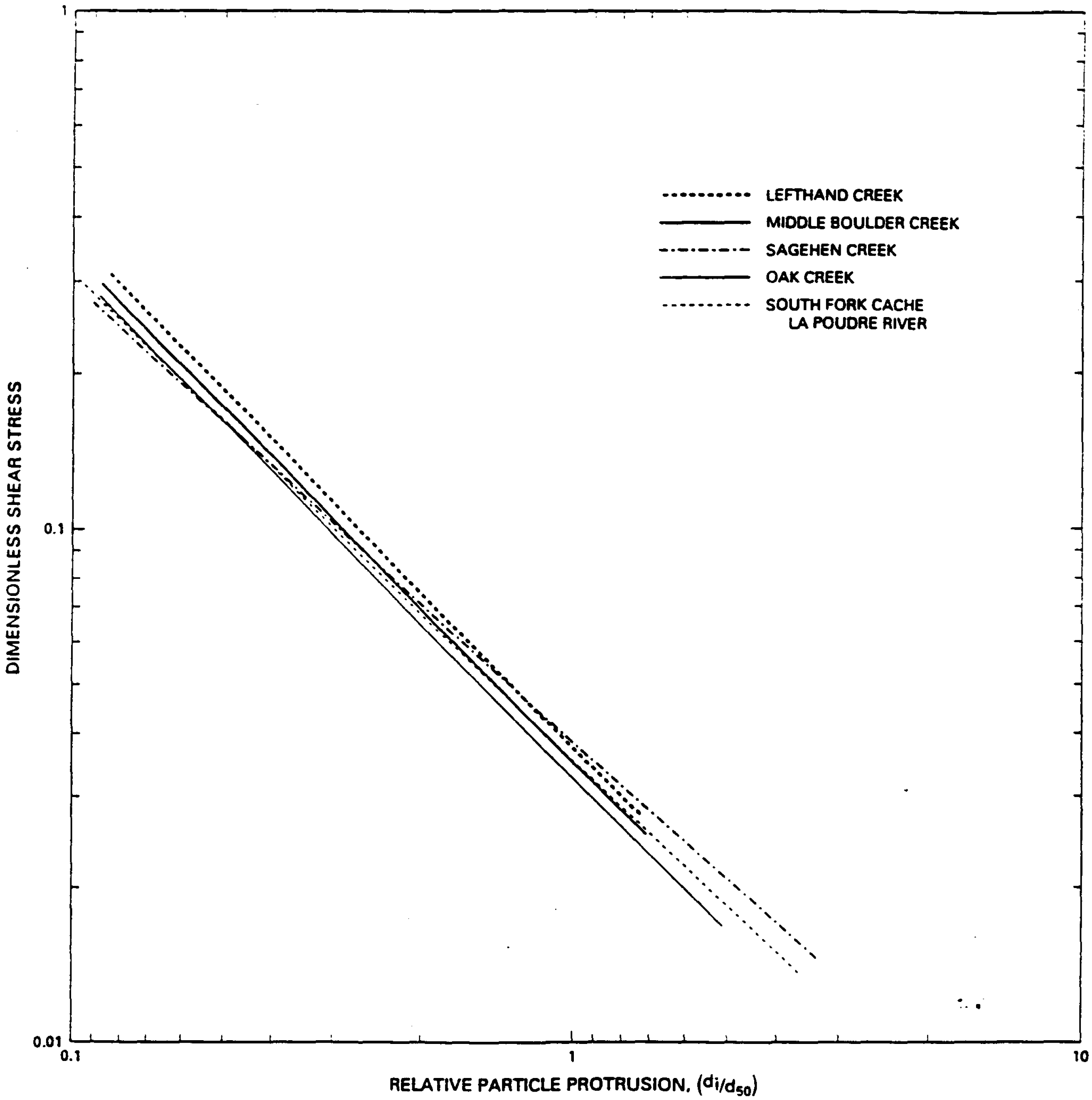
Figure 6. Number of days when streamflow within the range of dominant bed-material transporting discharge occurred on a given date

during the period of record, (a) Williams Fork nr. Leal; (b) North Platte River nr. Northgate; (c) Little Snake River nr. Slater; (d) Middle Boulder Creek at Nederland; (e) Lake Fork nr. Gateway; and (f) Halfmoon Creek nr. Malta.

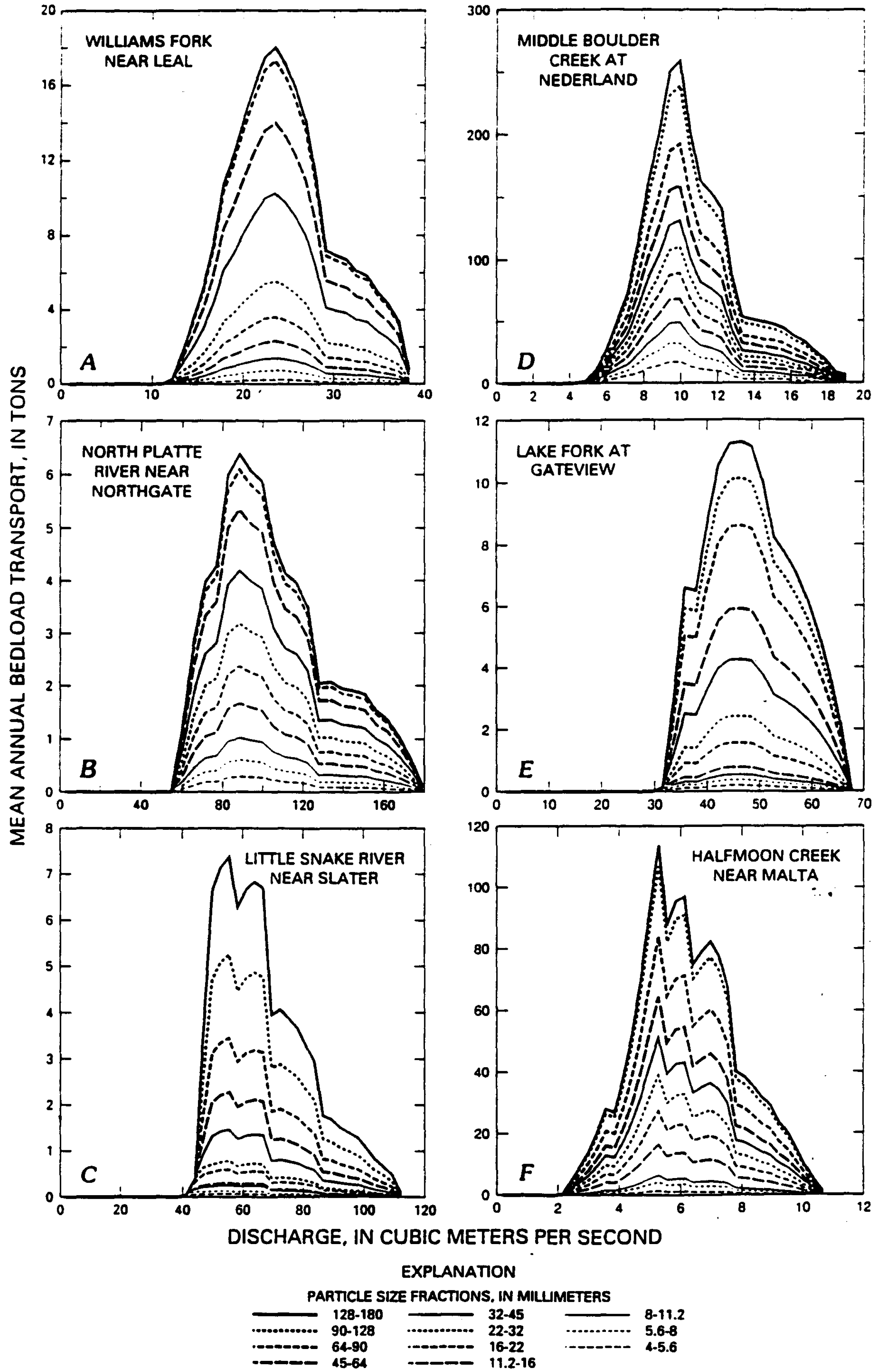
Figure 7. Channel maintenance flows determined for Middle Boulder Creek at Nederland during 3 years: (A) 1915, (B) 1954, and (C) 1957.

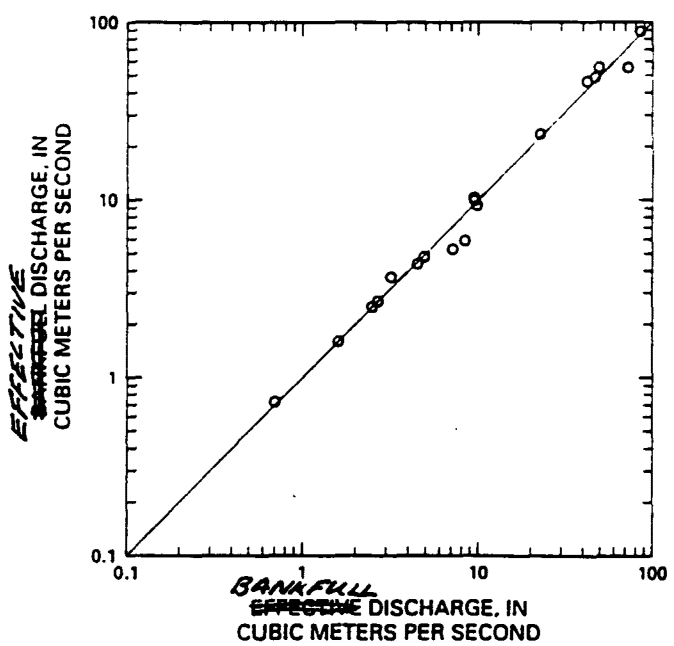


ANDREWS - FIG 01 - FIG01.AI - 08/09/94

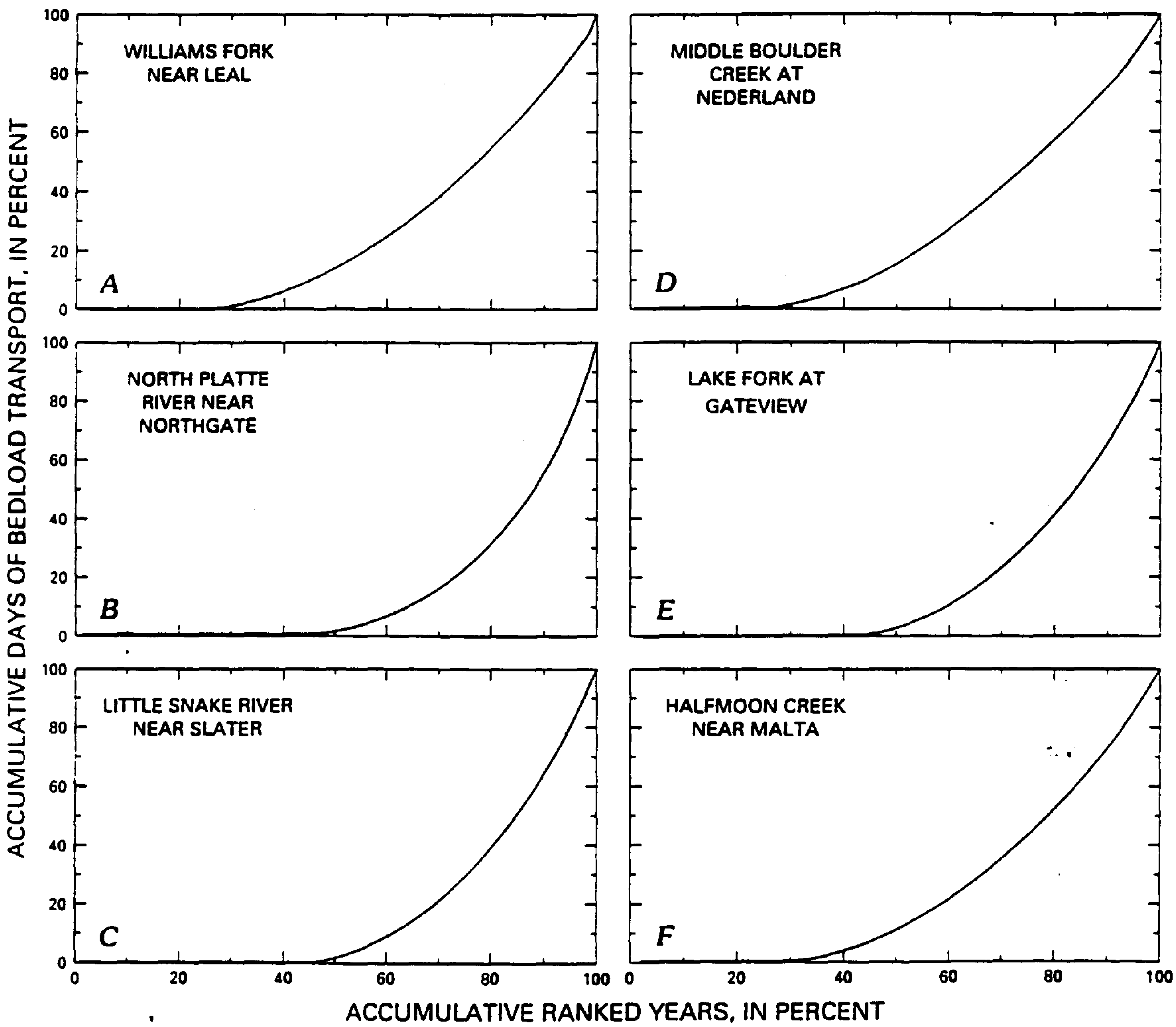


ANDREWS - FIG 02 - FIG02.AI - 08/09/94

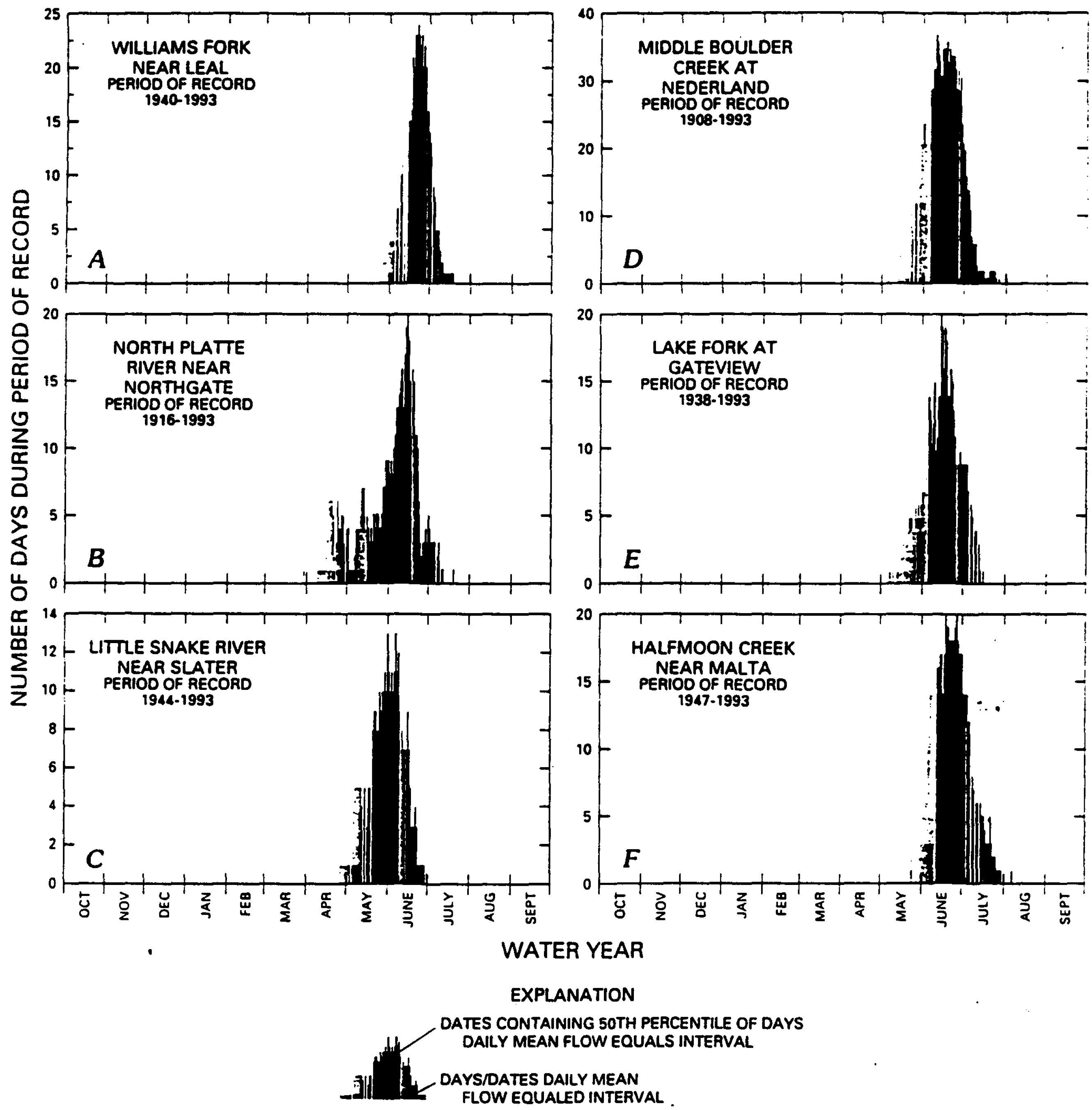

WILLIAMS FORK NEAR LEAL
A
MIDDLE BOULDER CREEK AT NEDERLAND
D
NORTH PLATTE RIVER NEAR NORTHGATE
B
LAKE FORK AT GATEVIEW
E
LITTLE SNAKE RIVER NEAR SLATER
C
HALFMOON CREEK NEAR MALTA
F
MEAN ANNUAL BEDLOAD TRANSPORT, IN TONS
DISCHARGE, IN CUBIC METERS PER SECOND
EXPLANATION
PARTICLE SIZE FRACTIONS, IN MILLIMETERS
128-180
90-128
64-90
45-64
32-45
22-32
16-22
11.2-16
8-11.2
5.6-8
4-5.6



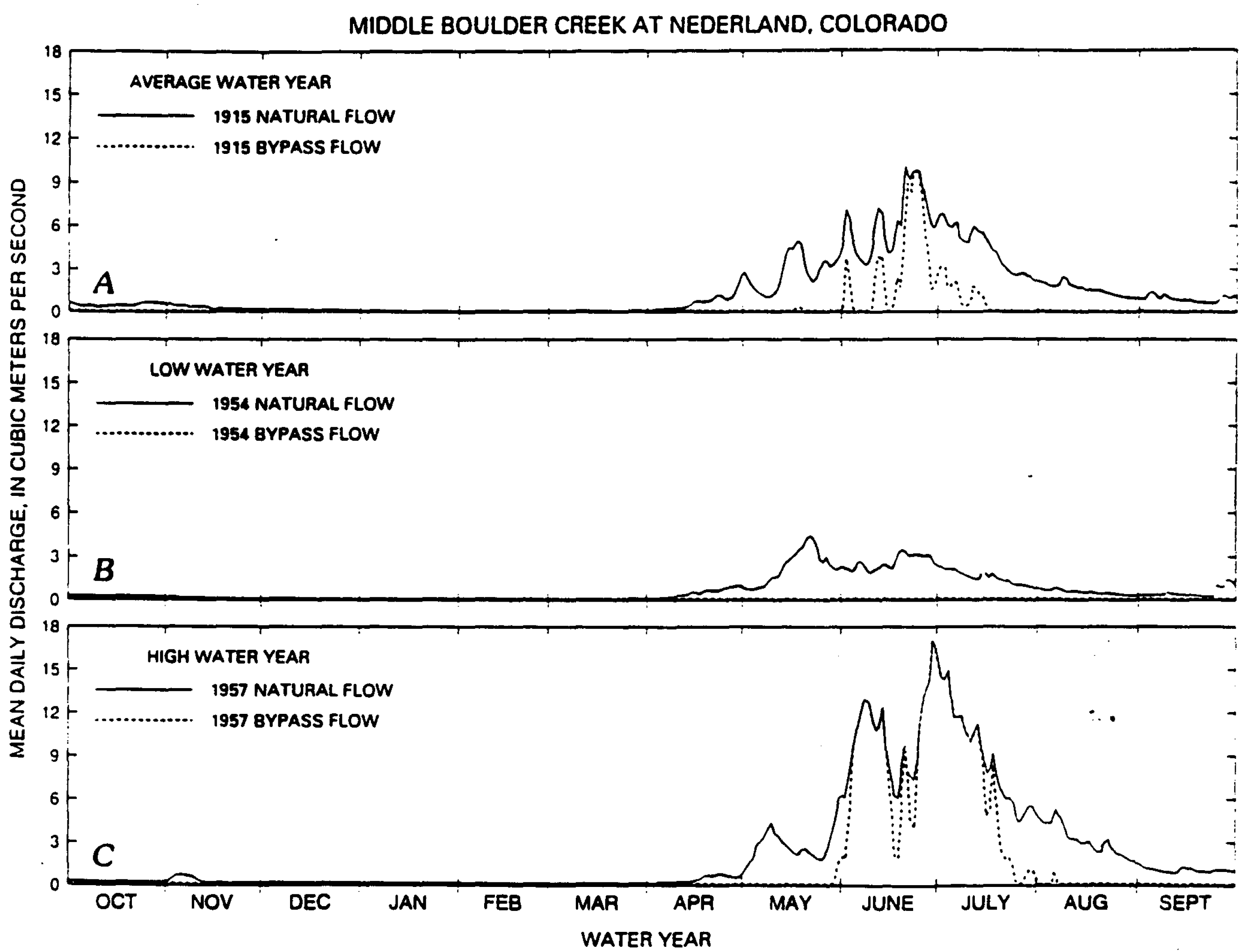
ANDREWS - FIG 04 - FIG04.AI - 08/09/94



ANDREWS - FIG 05 - FIG05.AI - 08/09/94



ANDREWS - FIG 06 - FIG06.AI - 08/09/94



ANDREWS - FIG 07 - FIG07.AI - 08/09/94